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Numerical Analyses and Flight Tests Verification for the Aerodynamic Characteristics of the Tilting Grille UAV

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Abstract: In this paper, according to the special layout of the tilting grille UAV, the aerodynamic characteristics of the UAV(unmanned aerial vehicle) was analyzed by CFD(computational fluid dynamics) method, and the result was validated through flight test. In CFD method, coordinate transformation and vector superposition were used to obtain the total aerodynamic force and moment characteristics, this method can substantially reduce the demand of computing resource. Based on the CFD result, the grille can reduce propeller actual pulling force, and the aerodynamic force and moment changed much. The flight test shows that the result of CFD can predict the flow characteristics and aerodynamic characteristics of the UAV during transition mode, and it can ensure the modeling precision for UAV flight control law design reference.

Key words: UAV, aerodynamic characteristics, numerical analyze, flight test

INTRODUCTION

The V-22 Osprey is the first production military tilt rotor aircraft. Tilt rotor aircrafts are recognized for their significant potential impact on both military and civilian aviation. At the same time with the same configuration of UAV has been developed quickly, the UAV fusions ability of helicopter hovering ability and fixed wing aircraft high level flight, which has the multi mission adaptability, and can be widely applied to the battlefield reconnaissance / surveillance task.

Compared with the conventional helicopter, tilt rotor aircraft has aerodynamic interference between rotor/wing/fuselage, which can have the adverse effect on the aerodynamic, control and stability properties, so foreign scholars carried out very early research on flow field interference. The way has two aspects (McVeigh *et al*., 1988; Felker *et al*., 1987): on the one hand, the wind tunnel test method, the cost is high, and the bracket, the wall will produce interference; on the other hand, the theoretical research method, the interference problem for the strong coupling, the rotor eddy theory (Mavris *et al*., 1989) has some limitations. Therefore, domestic and foreign scholars have switched to using the CFD method(Fejtek and Roberts, 1991). But CFD is also limited by the grid accuracy and processing speed of the computer (Potsdam and Strawn, 2002) used body fitted grid for solving N-S equation on the blade, and obtained the flow field characteristics of V-22, but the grid number is huge, and for the use of the nested grid, it needs a lot of computing resources.

Recently, the rotor fuselage aerodynamic interference study has achieved considerable development, By using free wake model the aerodynamic interference between the rotor and fuselage is studied (Zhao *et al*., 2000), further more by using free wake model coupled with the surface model, the interference problem of hovering rotor / wing aerodynamic is calculated(Li and Xu, 2008). The interference aerodynamics problems is very complex which need to be further studied.

According to the special layout of the tilting grille UAV, the aerodynamic characteristics of the UAV was analyzed by CFD method. For fixed wing mode and tilting grid separately modeling and meshing, the processing results obtained grille aerodynamic data and the whole aircraft aerodynamic which deducted grille (incompleted wing). At last, coordinate transformation and vector superposition were used to obtain the total aerodynamic force and moment characteristics, this method can substantially reduce the demand of computing resource. To verify the calculation results, the research group also were the scaled demonstration flight test was conducted.

CONFIGURATION OF THE TILTING GRILLE UAV

The typical variable flight mode with fixed wing UAV has high wing, single vertical tail, as shown in Fig. 1.

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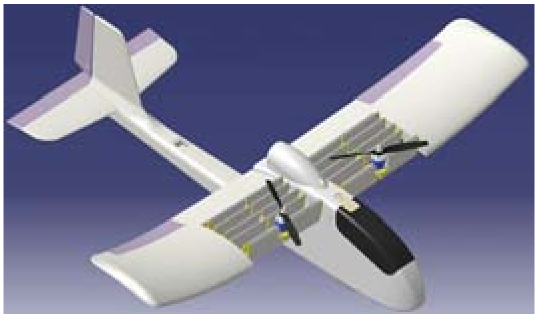

Fig. 1: Configuration of the tilting grille UAV

The UAV in the wing is arranged at the inner side of the tilting of the grid, the grille shape using the local wing section shape. Engine mounted in the grille, and grille linkage, can realize along the rotation axis to tilt 110 degrees range. When the flight mode conversion is processing, the grille can change the engine thrust line direction to control the UAV.

For the following calculation convenient description, this engine thrust line level forward, tilt angle is 0 degrees, vertical, inclined angle is 90 degrees. According to this definition, the inclination angle is 0 degrees, the corresponding fixed wing aircraft model, high-speed forward flight; the inclination angle is 90 degrees, the helicopter mode, the aircraft can hover, corresponding to the states in Fig. 1.

The tilting grid located in the wing inside, grille shape using the local wing section shape, grid is divided into three groups, each group in the 0 degrees to 110 degrees range rotate around the center shaft. In the 0 degrees grille inclination angle grid contour and airfoil coincide. The intent behind the grille tilt in Fig. 5.

When the UAV transits flight mode from the helicopter to the fixed wing, grid transition from 90 degrees to 0 degrees, the flow around a wing is dynamically changing with time.

NUMERICAL SIMULATION OF THE UAV AERODYNAMICS

Due to the special configuration of the tilting grille UAV, CFD is an effective method to obtain the aerodynamic parameters when the UAV transits flight mode from the helicopter to the fixed wing.

Governing equation: It is essential to work with the field solutions of Navier-Stokes equations, as shown in equation 1:

$$\frac{\partial U}{\partial t}+\frac{\partial F_i}{\partial x_i}=\frac{\partial G_i}{\partial x_i} \qquad (1)$$

Where

$$U=\begin{Bmatrix}\rho\\ \rho u_1\\ \rho u_2\\ \rho u_3\\ e\end{Bmatrix}\quad F_i=\begin{Bmatrix}\rho u_i\\ \rho u_1 u_i+p\delta_{1i}\\ \rho u_2 u_i+p\delta_{2i}\\ \rho u_3 u_i+p\delta_{3i}\\ (e+p)u_i\end{Bmatrix}\quad G_i=\begin{Bmatrix}0\\ \sigma_{1i}\\ \sigma_{2i}\\ \sigma_{3i}\\ u_m\sigma_{mi}+k\dfrac{\partial T}{\partial x_i}\end{Bmatrix}$$

ρ, p, e, T, k, σ_{mi} represent density, pressure, energy, temperature, coefficient of heat conduction and viscous shear stress respectively. u_i is the velocity component along the coordinate direction of x_i. The governing equations are discretized using the finite volume method.

Boundary condition: The computational far field is given velocity inlet, V=15m/s, H=300m.

The propeller slipstream velocity is 50m/s in the direction of the grid tilting.

Grid generation and flow field calculation: The block structured grid generation technique is used to simulate 3D flow field. Effect of different components on the aerodynamic characteristics of the whole UAV is analyzed.

In the pre-treatment of CFD calculation is about to generate the grid. Based on CAD software modeling, the computational surface and control mesh in IGES format are obtained. By using a commercial mesh generation software (GRIDGEN), the multi block grid is generated. The grid will be adjusted due to the computation result.

Computational grid is divided into the whole mesh and local grille mesh. There is a need to explain grille mesh consists of five types, corresponding to five different grid tilting angle, ϕ = 0°, 22.5°, 45°, 67.5° and 90°. Grid in each case is to separate generation.

The grid file is introduced into the Fluent software, and the simulation is began, until the residuals are converged.

At first, the whole machine's aerodynamic force and moment is obtained, and then the grille's aerodynamic force and moment is obtained, at last by the method of vector superposition the whole machine with the grille 's aerodynamic force and moment is achieved.

The state of computation as follow:

The longitudinal characteristics:

$$\alpha = -6° \sim 12°,\ \Delta\alpha = 3°,\ \beta = 0°,\ V = 15\text{m/s}$$

The lateral characteristics:

$$\alpha = 0°, 3°, 6°,\ \beta = -12° \sim 12°,\ \Delta\beta = 3°,\ V = 15\text{m/s}$$

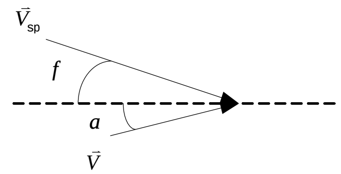

Fig. 2: The far field velocity and the slipstream velocity

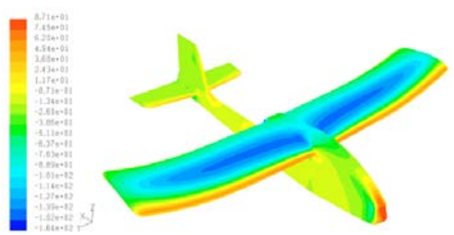

Fig. 3: The whole machine surface static pressure distribution

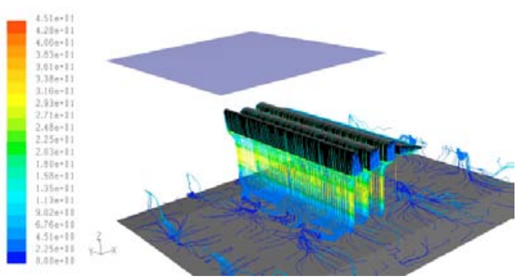

Fig. 4: Three-dimensional velocity traces aroud the grille

The grille characteristics:

$$\phi = 0°, 22.5°, 45°, 67.5°, 90°$$

Because the tilting grille is in the propeller slipstream region, the slipstream velocity is bigger than the far field velocity, so the latter is projected to the former ‘s direction as shown in Fig. 2.

The absolute angle of attack is defined as follow:

$$\alpha_{ab} = tg^{-1}\left(\frac{V\sin(\alpha+\phi)}{V_{slip} + V\cos(\alpha+\phi)}\right) \tag{2}$$

Where α represents the angle of attack, ϕ represents the tilting angle of the grille.

During calculation, the absolute angle of attack is changed from 0 degrees to 6 degrees.

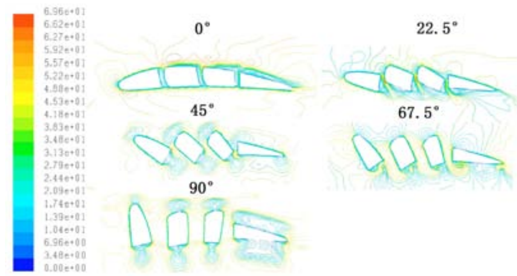

Fig. 5: the velocity distribution during grille tilting

Calculation result and analysis: The whole machine surface static pressure distribution as shown in Fig. 3, it can be seen from the figure, pressure distribution is in concordance with the conventional configuration aircraft, the CFD method can accurately simulate the fixed wing mode UAV under the flow field and aerodynamic characteristics.

From Fig. 4 separate grid three-dimensional velocity traces can be seen from the picture, the airflow through the grid gap, to the floor and ground bounce, roll up vortex, similar to the fountain effect.

Figure 5 is the velocity distribution during grille tilting angle at 0 degrees, 22.5 degrees, 45 degrees, 67.5 degrees and 90 degrees respectively. Although the grille to slip through, but the grille itself blocking effect on slip flow can not be ignored, this part of the resistance to the practical thrust propeller decrease.

The whole machine (without grille) aerodynamic characteristic: The whole machine (theory calculation of aerodynamic characteristics of wing) process in CFD, the grid position with airfoil instead, defined here as the theory of wing. Then the whole machine (without grille) aerodynamic can be seen as the whole machine subtracts the inner wing aerodynamic which can be shown as follow:

The whole machine (without grille) aerodynamic	=	The whole machine aerodynamic - the inner wing aerodynamic

So the whole machine(without grille) aerodynamic can be shown in equation 3:

$$\begin{cases} C_y = 0.0247\alpha + 0.1503 \quad (\alpha \le 4^\circ) \\ C_y = 0.0009\alpha^2 + 000244\alpha + 0.1445 \quad (4^\circ \le \alpha \le 9^\circ) \\ C_x = 0.3328C_y{}^2 - 0.0635C_y + 0.0233 \\ m_z = -0.1624C_y + 0.0395 \end{cases} \tag{3}$$

The grille aerodynamic characteristic: The characteristics of lift, drag and torque characteristics of the grille can be shown as follow:

ϕ = 0°

$$\begin{cases} C_{y2} = 0.0131\alpha + 0.0519 \quad (0^\circ \le \alpha \le 6^\circ) \\ C_{x2} = 0.0294C_{y2} + 0.0079 \\ m_{z2} = -0.032C_{y2} + 0.013 \end{cases} \quad (4)$$

ϕ = 22.5°

$$\begin{cases} C_{y2} = 0.0131\alpha + 0.0519 \quad (0^\circ \le \alpha \le 6^\circ) \\ C_{x2} = 0.0294C_{y2} + 0.0079 \\ m_{z2} = -0.032C_{y2} + 0.013 \end{cases} \quad (5)$$

ϕ = 45°

$$\begin{cases} C_{y2} = 0.0131\alpha + 0.0519 \quad (0^\circ \le \alpha \le 6^\circ) \\ C_{x2} = 0.0294C_{y2} + 0.0079 \\ m_{z2} = -0.032C_{y2} + 0.013 \end{cases} \quad (6)$$

ϕ = 67.5°

$$\begin{cases} C_{y2} = 0.0131\alpha + 0.0519 \quad (0^\circ \le \alpha \le 6^\circ) \\ C_{x2} = 0.0294C_{y2} + 0.0079 \\ m_{z2} = -0.032C_{y2} + 0.013 \end{cases} \quad (7)$$

ϕ = 90°

$$\begin{cases} C_{y2} = 0.0131\alpha + 0.0519 \quad (0^\circ \le \alpha \le 6^\circ) \\ C_{x2} = 0.0294C_{y2} + 0.0079 \\ m_{z2} = -0.032C_{y2} + 0.013 \end{cases} \quad (8)$$

These results can be used to calculate the aerodynamic force and pitching moment of transition mode of UAV. From the calculation results can be seen, along with the increase of the deflection angle of grille, grille drag coefficient increased significantly, especially from 45 ° to 67.5 ° deflection in the process, drag jump; lift coefficient at 0 ° maximum deflection angle, along with the increasing, lift coefficient decreased, which is due to the destruction caused by the integral wing profile.

The whole machine (with the grille) aerodynamic characteristic:

The whole machine (without the grille)'s lift Y_1 and drag Q_1 are defined in the body coordinate system $OX_{q1}Y_{q1}Z_{q1}$, but the grille's Y_2 and Q_2 are defined in the grille air coordinate system $O_2X_{q2}Y_{q2}Z_{q2}$.

In the grille air coordinate system $O_2X_{q2}Y_{q2}Z_{q2}$, the grille's lift and drag is described as:

$$\begin{cases} Y_2 = C_{y2}\dfrac{1}{2}\rho V_{SUM}^2\dfrac{S_2}{S} \\ Q_2 = C_{x2}\dfrac{1}{2}\rho V_{SUM}^2\dfrac{S_2}{S} \end{cases} \quad (9)$$

Where $\bar{V}_{sum} = \bar{V}_{sp} + \bar{V}$

The grille's lift and drag is transformed into the body coordinate system as follow:

$$\begin{bmatrix} Q_2' \\ Y_2' \\ 0 \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\phi & -\sin\phi & 0 \\ \sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\alpha_{ab} & \sin\alpha_{ab} & 0 \\ -\sin\alpha_{ab} & \cos\alpha_{ab} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} Q_2 \\ Y_2 \\ 0 \end{bmatrix} \quad (10)$$

And then the whole machine (with the grille) 's lift and drag can be described as:

$$\begin{cases} Y = Y_1 + Y_2' = C_{y1}\dfrac{1}{2}\rho V^2 S + Y_2' \\ Q = Q_1 + Q_2' = C_{x1}\dfrac{1}{2}\rho V^2 S + Q_2' \end{cases} \quad (11)$$

As the main lift component of the whole machine, when the wing is subtracted by the grille, the lift is severely declined., but with the grille and considering the slipstream, the lift is significantly increased. Application of this method can obtain the grille from 0 degrees to 90 degrees full range of deflection in the lift and drag properties. It will establish the original model reference data for the transition flight.

FLIGHT TEST

To validate the CFD results, we made scaled tilting grille UAV. The hovering helicopter mode and fixed wing mode flight test is carried out as shown in Fig. 6.

Test model and equipments: Test of the UAV is scaled 1:2.5, the use of, the whole machine weights 1.7 kg by

Fig. 6: Flight test at the hovering helicopter mode and fixed wing mode

Table 1: Changing of UAV's Aerodynamic Coefficients

	Project	Test result	Calculated	Error
Fixed wing mode	gravity/lift(N)	16.7	15.2	9%
	thrust/drag(N)	2.4	2.98	24%
Helicopter mode	Net drag/drag (N)	22-16.7=5.3	6.8	28%

using lightweight foam material. Rudder is mounted with electric actuator.

Experiments use artificial remote control mode, and there is stability augmentation device in the flight control system to ensure the safety of experiment. Parameters can be recorded during flight.

Flight test result: The result can be found in Table 1. From the data in Table 1 can be seen, CFD method to estimate the lift is more accurate, but the estimation of the drag value is too large, which can be modified with appropriate. Analysis of the causes, the calculation result of FLUENT itself is conservative, in addition, the surface roughness also result in deviation.

The flight test result shows that the aerodynamic of the grille model which is obtained by the CFD method is reasonable and effective, the CFD results for other transition mode of tilting grid of an UAV aerodynamic characteristics can be forecasted, These results can be used for dynamic control law design, which can ensure the accuracy of UAV modeling.

CONCLUSION

According to the special layout of the tilting grille UAV, the aerodynamic characteristics of the UAV was analyzed by CFD method. Coordinate transformation and vector superposition were used to obtain the total aerodynamic force and moment characteristics, this method can substantially reduce the demand of computing resource.

From the CFD results, the shield of the grille will reduce the actual pull propeller, which can affect the whole machine aerodynamic force and moment.

The helicopter mode and fixed wing mode scaling flight tests verify the CFD results, these results can also be used for flight control law design during transition mode.

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